Results from K2K and status of T2K*

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February 7, 2008

Abstract

Results from the K2K experiment and status of the T2K experiment are reported.

1 Results from the K2K experiment

The K2K experiment[1] is the first long-baseline neutrino oscillation experiment with a distance of hundred kilometers and using an accelerator-based neutrino beam. It started in 1999 and ended in November, 2004. The main purpose of K2K is to confirm muon neutrino oscillation claimed by the Super-Kamiokande experiment[2] using an artificial neutrino beam. Because the details of the experiment are already described in other articles[1, 3], only updated numbers and figures are presented in Table 1. Some comments that were not covered in my previous articles[3] are itemized below:

- After the accident of Super-Kamiokande in November, 2001, the total number of PMTs in Super-Kamiokande was reduced to be about one half. The K2K experiment of this period was named K2K-II. In this period, the lead-glass counters of the front detector were replaced by a SciBar detector[1], a fully active fine-grained detector made of 14848 strips of extruded scintillator read out by wavelength-shifting fibers. There is no essential change in the oscillation analysis.

- A possible ν_e appearance signal from $\nu_e \leftrightarrow \nu_\mu$ oscillation was also searched[4]. From tight e-like event selection, only one candidate remains, where the expected background is 1.63. The expected signal is $1 \sim 2$ events if the parameter region around the CHOOZ limit[5] is assumed. The 90% C.L. upper limit on $\sin^2 2\theta_{e\mu}$ $(=\frac{1}{2}\sin^2 2\theta_{13})$ is 0.18 for $\Delta m^2 = 2.8 \times 10^{-3}\mathrm{eV}^2$. This limit has no impact on our present knowledge on the oscillation parameters because of the poor statistics (see Section 3.1).

2 The T2K project: beamline and detectors

T2K (Tokai to Kamioka)[6] is the next long-baseline neutrino-oscillation experiment in Japan. A high-intensity neutrino beam from the J-PARC 50GeV Proton Synchrotron in JAEA, Tokai is shot toward Super-Kamiokande, 295 km away. Since all of these facilities, except Super-Kamiokande, are not familiar in the high-energy physics society, they are summarized in Table 2. A bird's eye view illustration of the entire J-PARC is shown in Fig. 1.

*Talk at International Conference on New Trends in High-Energy Physics (Crimea2005), Yalta, Ukraine, September 10-17, 2005.

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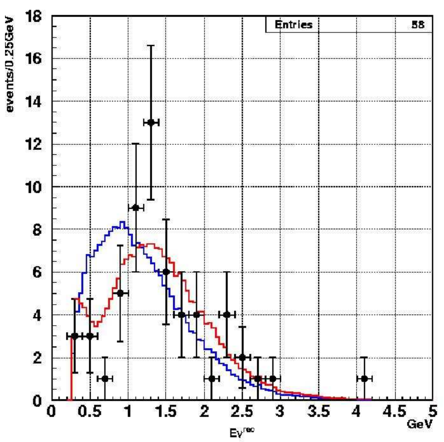
Table 1: Summary of the K2K results. For explanations of the numbers and figures, see [3]

• Beam period	Jun 4, 1999 - Jul 12, 2001 (K2K-I)
	Jan 17, 2003 - Nov 6, 2004 (K2K-II)
• Total beam time	442.8 days (233.7 for K2K-I + 209.1 for K2K-II)
• Total spill numbers	17.4×10^6 spills
• Total POT for analysis	92.2×10^{18}
• Total event (data/expectation)	112 / $155.9^{+13.6}_{-15.6}$
Single ring events	67 / 99.0
μ-like	58 / 90.8
e-like	9 / 8.2
(tight e-like cut)	(1) / (1.63)
Multi ring events	45 / 56.8
• Null oscillation probability	0.003%
• Best fit parameters in physical region	$(\Delta m^2,\sin^2 2\theta)$ =(2.76×10^{-3}eV^2,1.0)
• 90% C.L. Δm^2 for $\sin^2 2\theta = 1$	$(1.88 \sim 3.48) \times 10^{-3}$eV^2
• Reconstructed neutrino energy spectrum	• Allowed region in Δm^2-$\sin^2 2\theta$ plane



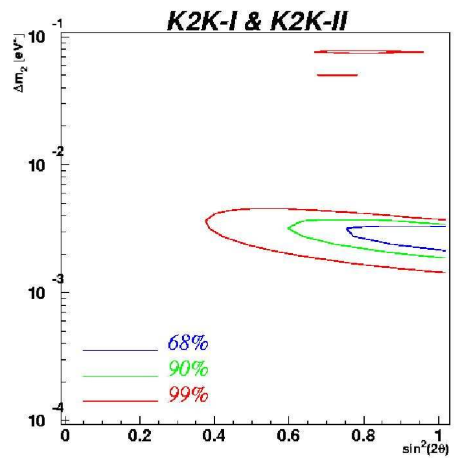


Table 2: Summary of the facilities and nicknames related to the T2K experiment.

J-PARC	Japan Proton Accelerator Research Complex. The name of the entire project. It includes high energy physics, nuclear physics, life science, material science and nuclear technology. The Accelerators consist of 400MeV Linac, 3 GeV Proton Synchrotron and 50GeV proton Synchrotron.
JAEA	Japan Atomic Energy Agency. Host institute of J-PARC. KEK is the second host institute. Renamed from JAERI (Japan Atomic Energy Research Institute) on October 1, 2005.
Tokai	Name of the village where JAEA is located. About 110km north-east from Tokyo
JHF	Japan Hadron Facility. Name of the 50GeV Proton Synchrotron project.
T2K	Tokai to Kamioka. Name of the long-baseline neutrino-oscillation experiment. It was also called JHF-ν or J-PARC ν

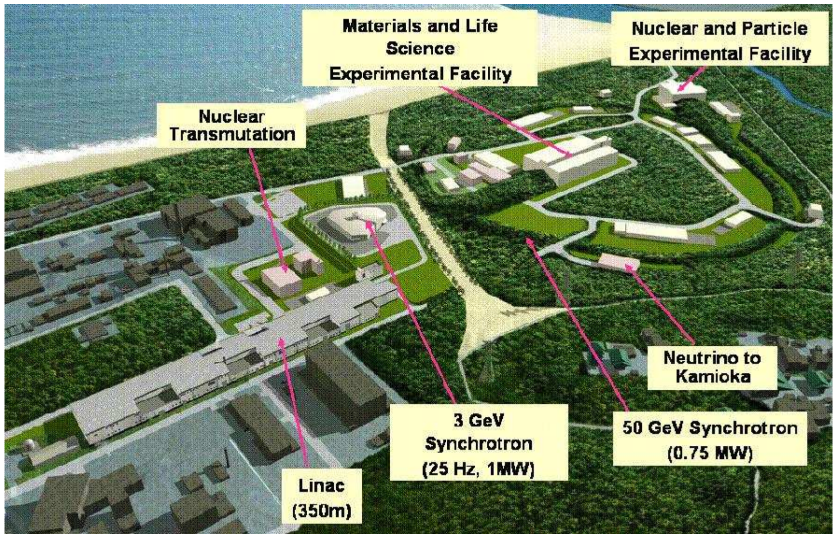


Figure 1: Bird's eye view of the entire J-PARC project.

J-PARC has been under construction since 2001. The T2K experiment was officially approved in December, 2003, except for the 2-km detector discussed below. Construction of the neutrino beamline started in April, 2004. The experiment will start in early 2009.

Schematic configurations of the T2K beamline and detectors are illustrated in Fig. 2. They consist of the proton beamline, target station, decay volume, beam dump, muon monitors at 140 m downstream from the target, first front detectors at 280 m, second front detectors at 2 km, and Super-Kamiokande as a far detector at 295 km. The main differences from the K2K experiment are: (1) very high beam intensity, (2) off-axis beam and (3) 2 km detector. In the following, these three main differences are focused on one by one.

2.1 High-intensity proton beam

The most significant upgrade from the K2K experiment is the beam intensity. The beam power of T2K in the first stage is 0.75 MW. It is more than 2 orders of magnitude larger than that of K2K. A further upgrade of the beam intensity after several years of 0.75 MW operation is also under consideration. Comparisons of the beam parameters between the K2K, T2K and T2K upgrade are summarized in Table 3

The number of neutrino events in T2K is about 110-times larger than that of K2K. This high-statistics observation enables searches for unknown oscillation channels as well as precise

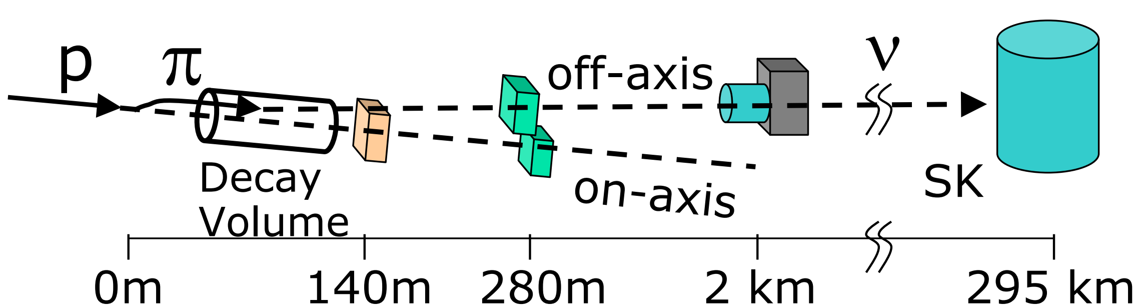


Figure 2: Schematic configuration of the T2K beamline and detectors.

Table 3: Comparisons of the beam parameters between K2K and T2K. For the neutrino events in Super-Kamiokande, 22.5kton is the fiducial mass and one year is taken as 100 days. The absence of neutrino oscillation is assumed, and the number for K2K was calculated from 155.9events/442.8days (see Table 1). For T2K, a 2° off-axis angle is assumed. Some of the parameters in the T2K upgrade are still being designed.

	K2K	T2K	T2K upgrade
Proton Energy (GeV)	12	50	50
Beam power (kW)	5.2	750	4000
Proton per second	3×10^{12}	1×10^{14}	5×10^{14}
Accelerator cycle (sec)	2.2	3.64	
Beam duration (μsec)	1.2	4.2	
Neutrino events in SK (/22.5kton/year)	35	3900	

determinations of the oscillation parameters in $\nu_\mu \leftrightarrow \nu_\tau$.

2.2 Off-axis beam

Off-axis beam[7] means that the center of the beam direction is adjusted to be $2^\circ \sim 3^\circ$ off from the Super-Kamiokande direction, as shown in Fig. 2. Although the neutrino beam intensity at Super-Kamiokande is lower than that of the beam center (on-axis) direction, the peak energy is low and high-energy neutrinos are strongly suppressed. The neutrino energy spectra for several off-axis angles are shown in Fig. 3. An off-axis beam is favored because a neutrino energy lower than $\sim$1 GeV is preferable in the T2K experiment for the following three reasons:

The first reason is the neutrino oscillation probability. The probability that ν_μ remains as ν_μ is written as

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{23} L}{E_\nu}\right), \tag{1}$$

where L is the neutrino travel distance (L = 295km) and E_ν is the neutrino energy. $P(\nu_\mu \to \nu_\mu)$ as a function of E_ν is also shown in Fig. 4. The neutrino energy, which corresponds to the first oscillation maximum, E_{oscmax}, is obtained from

$$\frac{1.27\Delta m^2_{23} L}{E_{oscmax}} = \frac{\pi}{2} \tag{2}$$

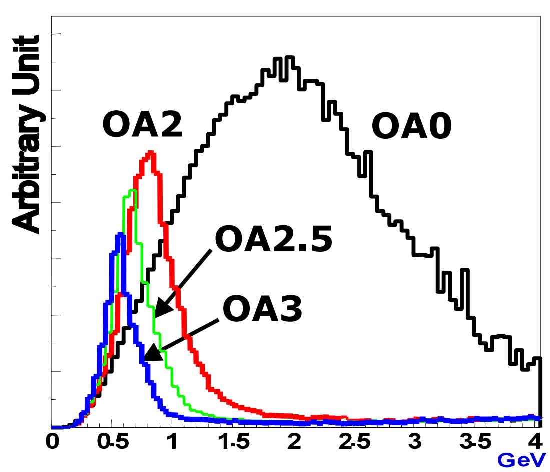


Figure 3: Neutrino energy spectrum for several off-axis angles.

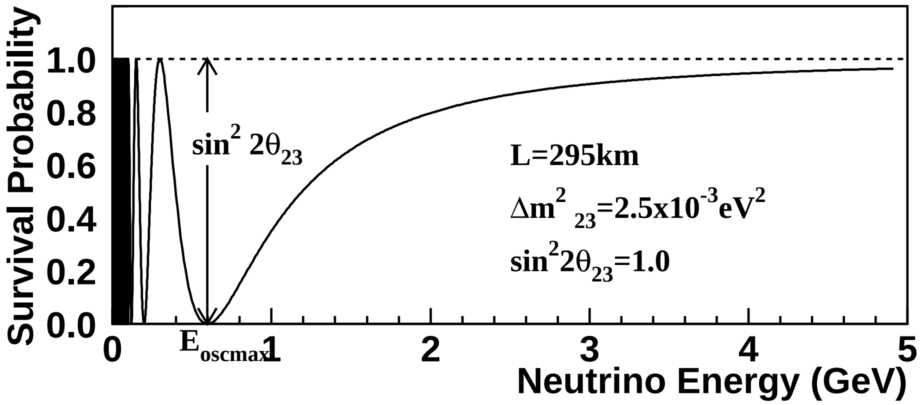


Figure 4: Survival probability of muon neutrinos as a function of the neutrino energy. The neutrino travel distance is 295 km and oscillation parameters are assumed to be $(\Delta m^2_{23}, \sin^2 2\theta_{23}) = (2.5 \times 10^{-3}\mathrm{eV}^2, 1.0)$.

or

$$E_{oscmax} = \frac{2.54\Delta m^2 L}{\pi}. \tag{3}$$

$E_{oscmax} = 0.596$GeV for $\Delta m^2 = 2.5 \times 10^{-3}\mathrm{eV}^2$ and $E_{oscmax} = 0.834$GeV for $\Delta m^2 = 3.5 \times 10^{-3}\mathrm{eV}^2$. If the neutrino beam energy agrees with E_{oscmax}, the oscillation occurs effectively, and a study of neutrino oscillation is also efficient.

The second reason is the fraction of the charged-current quasi-elastic scattering (CCQE) in the neutrino interactions. As reported in K2K[1], the neutrino energy spectrum is obtained from CCQE interactions,

$$\nu_\mu + n \to \mu^- + p, \tag{4}$$

calculated by simple 2-body kinematics

$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}, \tag{5}$$

where m_N and m_μ are the masses of the nucleon and the muon, respectively, and $E_\mu = \sqrt{p_\mu^2 + m_\mu^2}$. Other neutrino interactions cannot be used for this purpose because of complex kinematics. Moreover they constitute serious background when CCQE events are selected. The neutrino cross section and the contribution of CCQE interactions are shown is Fig. 5. Although neutrinos of energy larger than $\sim$1 GeV have larger total cross sections, most of the interactions are non-CCQE and disturb the determination of neutrino energy spectrum.

The third reason is related to the second reason, but concerns the nature of water Cherenkov detectors. Water Cherenkov detectors show excellent performance for single ring events or multiple ring events in which particles forward to opposite directions and the Cherenkov rings do not overlap with each other. On the other hand, it does not have good performance for events with heavy ring overlapping. High-energy ($E_\nu \gtrsim 1$ GeV) neutrinos that produce multiple rings are not preferable in water Cherenkov detectors.

The best off-axis angle implies that the peak of the neutrino energy spectrum is exactly in accordance with the oscillation maximum. See Table 4 for the relation between the off-axis angle, the peak of the neutrino energy and the corresponding Δm^2_{23}. Unfortunately, the Δm^2_{23} values

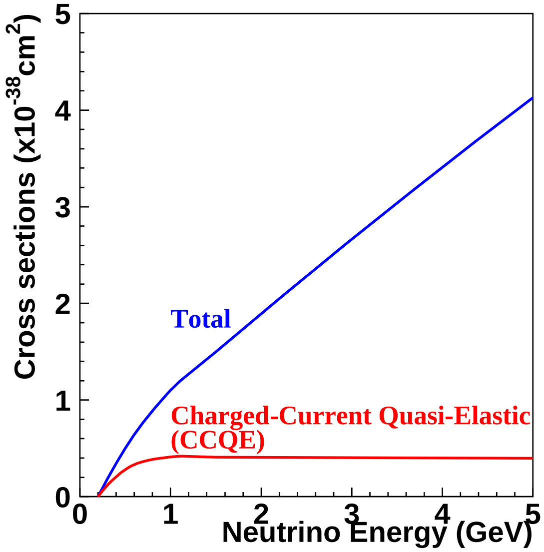


Figure 5: Neutrino cross section and the fraction of CCQE as a function of the neutrino energy.

reported by other experiments[1, 2] have large ambiguity, and the best off-axis angle is still unknown. For this reason, we must maintain the tunability of the off-axis angle until just before the commissioning of the neutrino beam.

We are constructing a decay volume having a special shape, as shown in Fig. 6. The cross section of the decay volume is rectangular and the height of the volume is becoming larger downstream. The cross section in the most downstream part is 3 m (width) $\times$ 5.43 m (height). If the position of the beam center is adjusted to 1.50 m (3.93 m) below the top of the decay volume, the direction of the Super-Kamiokande and Hyper-Kamiokande[6, 8] is $2.0^\circ(3.0^\circ)$ off-axis, as shown in Fig. 6. The direction of the beam center can be adjusted by arranging the magnets in the final focusing section and target/horn in the target station. Civil construction is not required. We can determine the beam direction about a half year before the beam commissioning which is scheduled for early 2009. Hopefully, we can decide the exact beam direction in the summer of 2008, after hearing about the latest result from the MINOS[9] experiment, reported at the 2008 summer conferences.

2.3 The 2 km detector

We have proposed to construct second front detectors at about 2 km from the proton target for the following two reasons.

The first reason is related to the off-axis beam. For reliable neutrino flux extrapolation from the front detectors to the far detector, the 110 m of the neutrino production point (i.e. decay volume) must be viewed as "point like" from the front detectors. At the 280 m detector with a 2.5° off-axis position, the angular difference between the neutrino from the most upstream part of the decay volume and the most downstream part is about 1.6°. Obviously, this angular difference

Table 4: Off-axis angle, peak of the neutrino energy spectrum and the corresponding Δm^2 for a neutrino travel distance of 295 km, which were calculated from $E_{oscmax} = E_{peak}$.

Off axis angle	2.0°	2.1°	2.4°	3.0°
E_{peak} (GeV)	0.782	0.756	0.656	0.520
$\Delta m^2_{23}(\times 10^{-3}\mathrm{eV}^2)$	3.28	3.17	2.75	2.18

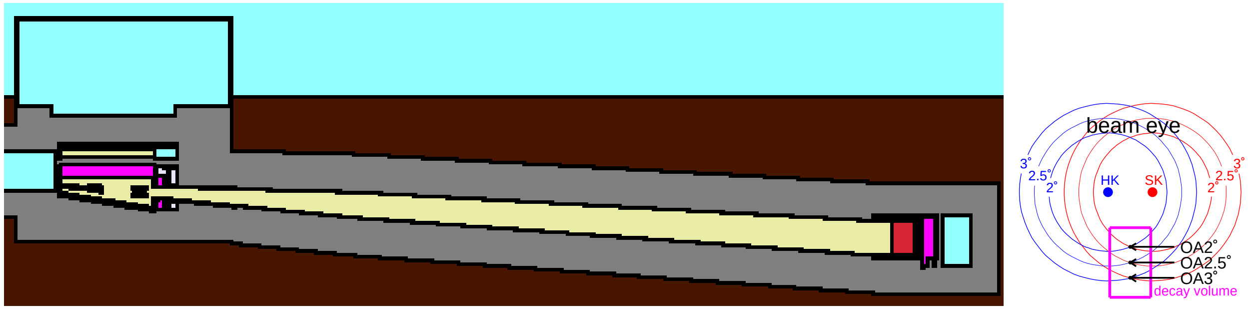


Figure 6: (left) Schematic view of the target station, decay volume and beam dump. The height of the decay volume is becoming larger in the downstream region in order to change the direction of the beam center. (right) Cross section view of the decay volume and the directional correlation with Super-Kamiokande and Hyper-Kamiokande.

is not negligible. The 280 m detector site is too near to the neutrino production point.

The other reason is the water Cherenkov detector as a front detector. A water Cherenkov detector is definitely needed as a front detector because the detection technique is exactly the same as the far detector, and most of the systematic errors inherent to the detector can be canceled out. However, we have a serious difficulty with the event rate. If a 1 kt water Cherenkov detector (the same size as K2K) is constructed at the 280 m site, the event rate will be about 60 events per one spill, which is a 4.2 μsec beam duration. This event rate is much larger than the capacity of the water Cherenkov detector.

Because of these reasons, we decided to construct second front detectors, whose main component is a water Cherenkov detector outside of the JAEA campus. From physics constraints as well as a problem concerning estate ownership, we proposed them to be located at about 2 km away from the target. This 2 km detector was not included in the first proposal, and has not yet been approved.

3 Physics goal of T2K

If neutrinos have mass, the flavor eigenstates are a mixture of the mass eigenstates:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathbf{U} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}. \tag{6}$$

The neutrino mass matrix, $\mathbf{U}$, has 6 independent parameters. They are 2 square mass differences (Δm^2_{12} and Δm^2_{23}), 3 mixing angles (θ_{12}, θ_{23} and θ_{13}) and 1 CP-violation phase (δ).

Among 6 parameters, Δm^2_{12} and θ_{12} were determined by solar neutrino experiments[10, 11] and a reactor experiment[12]. At present, their values are

$$\Delta m^2_{12} = (6 \sim 8) \times 10^{-5}\mathrm{eV}^2 \quad \text{and} \quad \sin^2 2\theta_{12} \approx 0.8. \tag{7}$$

On the other hand, Δm^2_{23} and θ_{23} were studied by using atmospheric neutrinos[2] and long-baseline accelerator neutrinos[1]. The present values are

$$\Delta m^2_{23} = (2 \sim 3) \times 10^{-3}\mathrm{eV}^2 \quad \text{and} \quad \sin^2 2\theta_{23} \gtrsim 0.9. \tag{8}$$

Accordingly, unknown oscillation parameters are θ_{13} and δ.

The physics goal of the T2K experiment is a complete understanding of the neutrino-oscillation parameters. It includes: (1) the first observation of finite θ_{13}; (2) precise measurements of Δm^2_{23} and θ_{23}; (3) observation of the CP violation phase δ after a beam-intensity upgrade from 0.75 MW to 4MW and construction of Hyper-Kamiokande. The third topic will not occur within the next decade, and is thus beyond the scope of this document. Only the first and second items are discussed below.

3.1 $\nu_e \leftrightarrow \nu_\mu$ oscillation

Within the framework of 3-flavor oscillation, the oscillation probability of ν_μ to ν_e with the θ_{13} channel is written as

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Big(\frac{1.27\Delta m^2_{23}L}{E_\nu}\Big). \tag{9}$$

In past neutrino oscillation searches, Δm^2 and $\sin^2 2\theta$ were simultaneously searched for in the Δm^2-$\sin^2 2\theta$ plane. On the contrary, in the θ_{13} search, other parameters in the oscillation probability have almost been determined from the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation, as given in Eq.(8).

From a theoretical point of view, θ_{13} is expected to be small because it is the mixing angle between the first and third generation. In fact, the present upper limit reported by the CHOOZ experiment[5] is $\sin^2 2\theta_{13} \sim 0.1$. Even though the energy of the neutrino beam is adjusted to E_{oscmax} based on knowledge of the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation,

$$P(\nu_\mu \to \nu_e) \approx \frac{1}{2}\sin^2 2\theta_{13}\sin^2\Big(\frac{1.27\Delta m^2_{23}L}{E_\nu}\Big) < 0.05, \tag{10}$$

where $\sin^2\theta_{13}$ is taken as $\sim$1/2 from Eq.(8). Therefore, an appearance search of electron neutrinos with a probability of less than a few percent is necessary to find a finite θ_{13}. Obviously, the statistics of K2K was too poor to examine such a small oscillation probability (see [4] and the first section).

More than 100-times larger statistics in T2K makes a search for such a small oscillation probability possible. Furthermore, in addition to the analysis procedure in K2K, constraints on the electron neutrino energy can be applied in selecting the ν_e appearance signal, because the parent neutrino energy calculated from Eq.(5) (by replacing muon by electron) has a quasi-monochromatic energy spectrum, as discussed in Section 2.2.

From a careful Monte-Carlo study, about $\sim$100 ν_e signals are expected, whereas the background from the neutral current and the beam-originated ν_e are less than 15, if the oscillation parameter is assumed to be $\sin^2 2\theta_{13} = 0.1$ with 5×10^{21}POT. The nominal sensitive region is

$$\sin^2 2\theta_{13} > 0.006. \tag{11}$$

This improves the sensitive region from the CHOOZ experiment by a factor of $\sim$20.

3.2 $\nu_\mu \leftrightarrow \nu_\tau$ oscillation

Precise determinations of Δm^2_{23} and $\sin^2 2\theta_{23}$ were attained by precise measurements of the neutrino survival probability as a function of the neutrino energy given in Fig. 4.

Δm^2_{23} is directly determined from the position of the oscillation maximum (E_{oscmax}) from Eq.(3). From $\sim$5% accuracy of the E_{oscmax} measurement, Δm^2_{23} is also determined with $\sim$5% accuracy. Since $\Delta m^2_{23} = (2 \sim 3) \times 10^{-3}\mathrm{eV}^2$,

$$\delta(\Delta m^2_{23}) \sim 0.1 \times 10^{-3}\mathrm{eV}^2 \tag{12}$$

is possible.

On the other hand, $\sin^2 2\theta_{23}$ is determined from the depth of the dip at E_{oscmax} in the neutrino survival probability (see Fig. 4) and/or the absolute reduction rate of muon neutrino events.

Because more than 10000 neutrino events are expected within 5 years of operation, the statistical error for the event rate is reduced to be about 1%. Therefore,

$$\delta(\sin^2 2\theta_{23}) \sim 0.01 \tag{13}$$

is expected.

The author is grateful to the members of K2K and T2K collaborations for fruitful discussions.

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